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PRESENT AND PROSPECTIVE TECHNOLOGY FOR PREDICTING SEDIMENT YIELDS AND SOURCES

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SEDIMENT YIELD AS RELATED TO A STOCHASTIC MODEL OF EPHEMERAL RUNOFF

By K. G. Renard and L. J. Lane[1]

Ephemeral streams in areas subject to air-mass thunderstorms characteristically have highly variable runoff. Quantification of such runoff is difficult but necessary before the sediment yield of a watershed can be estimated.

Provisions for sedimentation processes should be an integral part of design, construction, or maintenance of conservation measures in a watershed. Although progress has been made toward understanding the processes of sedimentation, such as the detachment, entrainment, transport, deposition, and consolidation of fluvial sediments, much work remains. We believe that significant progress toward predicting sediment yield can be made by coupling hydrologic models (or phases of the hydrologic cycle) to analytical models of sedimentation processes.

Sedimentation and hydrologic processes have essential similarities in humid and arid areas, but there are major differences involved in their boundary conditions. Figure 1 shows that conceptually, even with tributary inflow, the discharge of an ephemeral stream may remain the same or decrease downstream because of the continual water loss to the coarse streambed. Such losses in ephemeral streams may dominate the streamflow response to precipitation events. Although transmission losses in ephemeral channels has been discussed extensively (*1, 2, 5, 6, 11, 12, 14, 15, 19, 20, 21, 24*),[2] satisfactory analytic models for use on ungaged basins within a region are not yet available.

As an alternative to determining the runoff at a specific point and then routing it in time and space, certain runoff properties can be quantified by modeling the runoff as a stochastic process. Data on storm occurrences in time and space and magnitudes of the individual events are necessary for a model relating runoff and sediment yield. A stochastic model that preserves the special conditions encountered in ephemeral streams in semiarid regions can be developed.

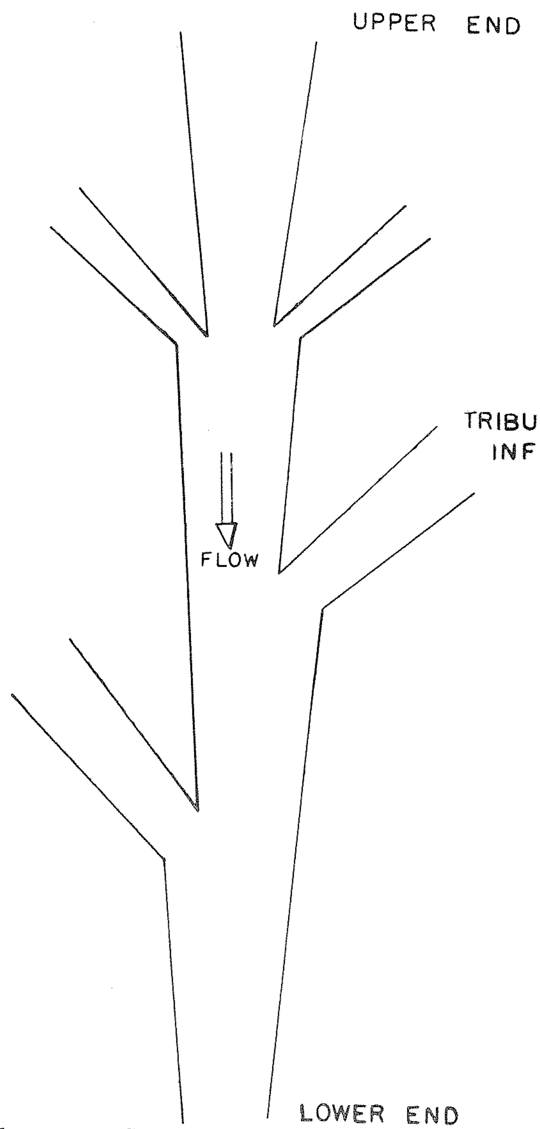

FIGURE 1.—Conceptual model of an ephemeral stream reach with discharge porportional to stream width.

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[2] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this paper.

DESCRIPTION OF WATERSHED

The sediment-yield model described in this paper incorporates a stochastic model of runoff with a deterministic sediment-transport relation. It was developed and verified with field data for the Walnut Gulch Experimental Watershed near Tombstone in southeastern Arizona (fig. 2). The watershed, which is operated by the Agricultural Research Service, contains 95 recording rain gages and 11 major, critical-depth, streamflow measuring stations. The 58-mi² watershed has an average annual precipitation of 14 inches and is representative of much of the mixed grass-bush rangeland in southeastern Arizona and southwestern New Mexico. Most of the watershed is grazed year around. Elevations in the watershed range from 4,000 ft above mean sea level at the watershed outlet to over 6,000 ft. Most of the watershed consists of gently rolling, low hills typical of the intermountain Basin and Range province, with only about 1 mi² of the watershed in the headwaters of the Little Dragoon Mountains.

STOCHASTIC MODEL OF RUNOFF

Techniques have been developed for using stochastic models in water-resource systems (*10*). Maass et al. (*18*) suggested the use of synthetic data to partially overcome the problem of short-duration data. Benson and Matalas (*3*) used statistical parameters estimated from the physical and climatic characteristics of drainage basins to generate data at ungaged locations. More relevant to analysis of runoff on semiarid areas such as Walnut Gulch is the work of Kisiel, Duckstein, and Fogel (*13*) concerning the analysis and modeling of ephemeral streamflow. Further analysis (*9*) related rainfall and runoff for summer storms. In their analysis, a Poisson distribution was used to model the number of events per season. The assumption of a Poisson distribution was based on the work of Brooks and Carruthers (*4*) and Todorovic and Yevjevich (*22*). Duckstein, Fogel, and Kisiel (*9*) modeled the rainfall depth at a point as a geometric random variable and the areal rainfall as a negative binomial random variable. The runoff volumes were obtained by assuming a linear rainfall-runoff relationship and then randomizing the coefficient.

As an alternative to a rainfall-runoff model, a stochastic model of ephemeral runoff was developed with data from the Walnut Gulch Experimental Watershed (*7, 8, 16*). This stochastic model, which is summarized in figure 3 and table 1, generates intermittent and independent runoff events and was used as a starting point for the study reported here. Two variables were used to describe the runoff season: (1) the starting date of the summer runoff season and (2) the number of runoff events recorded at the watershed outlet per season. The temporal distribution of the runoff events was described by two variables: (1) the event time of day and (2) the interval between events. Each runoff event was described by two random variables: (1) runoff volume and (2) peak discharge. Runoff volume and peak discharge were highly correlated so that the peak discharge could be generated from the runoff volume. The synthetic data generation process is shown in figure 3. A final characterization of the model is given by the assumed distributions for the random variables. These assumed distributions, modified from Diskin and Lane (*8*), are given in table 1.

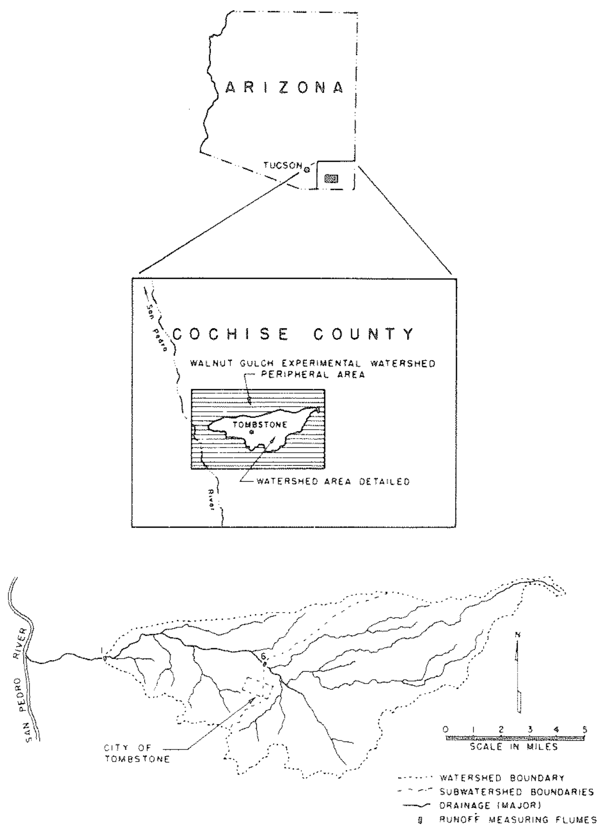

FIGURE 2.—Walnut Gulch Experimental Watershed.

TABLE 1.—*Assumed probability distributions for variables describing runoff events*

Runoff variable	Symbol	Theoretical distribution	Parameters
Start of runoff season	S	Normal	Mean, standard deviation.
Number of events at outlet per runoff season.	N	Poisson	Mean.
Begin time of each event	T	Normal	Mean, standard deviation.
Interval between events	D	Negative exponential.	Mean.
Logarithm of volume of runoff for each event.	L	Normal	Mean, standard deviation (of logarithms).

SEDIMENT-TRANSPORT MODEL

The sediment-transport part of the sediment-yield model was developed with the Manning equation and the Laursen (*17*) transport relation, given respectively as

$$V=\frac{1.49}{n}R^{2/3}S^{1/2}, \quad (1)$$

where V=average velocity in feet per second,
n=Manning's roughness coefficient,
R=hydraulic radius in feet,
and S=slope of bed in feet per foot,

$$\text{and } \overline{C}=\sum^{p}\left[p\left(\frac{d}{y}\right)^{7/6}\left(\frac{\tau_0'}{\tau_c}-1\right)f\left(\frac{\sqrt{\tau_0/\rho}}{w}\right)\right], \quad (2)$$

where C=the mean concentration of total sediment in percent by weight,
p=bed material fraction of diameter d,
d=diameter of sediment particle in feet,
y=depth of flow in feet,
τ_0'=boundary shear stress associated with sediment diameter,
τ_0=boundary shear or tractive force at the stream bed=$\gamma y S_0$,
τ_c=critical tractive force for the beginning of sediment movement,
γ=mass weight of water in pounds per cubic foot,
ρ=density of water in slugs per cubic foot,
and w=fall velocity of sediment in feet per second.

With the Manning formula and the Strickler expression for n as a function of the sediment diameter ($n=0.034d^{1/6}$) it can be shown that

$$\tau_0'=KV^2\left(\frac{d}{y}\right)^{1/3}, \quad (3)$$

where $K=1/30$ and $d=D_{50}=\mu$, the mean grain size.

The critical tractive force was obtained by Laursen as

$$\tau_c=Cd, \quad (4)$$

where, from the Shields diagram, $4\leq C\leq 16$.

The function term in the formula can be determined graphically or by writing straight-line equations for segments of the u^*/w relationship given in Laursen's original paper. For the digital-computer solutions used subsequently, a linear interpolation scheme was developed with logarithms of the data for straight-line segments of the original graph. The fall velocity for the sediment was computed with a similar logarithmic interpolation scheme for data from figure 5 of reference 23.

The instantaneous sediment discharge (assuming a bulk dry sediment weight of 100 lb/ft^3) for a given water discharge was obtained by Laursen from the equation

$$q_s=\frac{\overline{C}q}{265}, \quad (5)$$

where q_s=instantaneous sediment discharge in cubic feet per second per foot of stream width,

q=instantaneous water discharge in cubic feet per second per foot of stream width,

and $\overline{C}$=mean sediment concentration in percent by weight.

Many ephemeral streams have wide cross sections with relatively level bottoms. Such wide sections and relatively shallow flow depths relative to the channel width allow approximating the hydraulic radius with the flow depth (y). Further simplification can be made by assuming that the flow cross section can be approximated by a rectangular section where area is the product of the top width and the flow depth, the relationship used in equation 5. With these assumptions and equations, a computer program was developed to facilitate the computations. A flow chart for this program is shown in figure 4.

To compute the sediment-discharge volume associated with each runoff event, a triangular hydrograph shape was assumed. To minimize the computing time, discharge-concentration computations were based on the value of Q_p/b, with a simple triangle assumed when Q_p/b was less than unity (b is the stream width in feet). When Q_p/b was less than 10, the concentration was obtained at the hydrograph peak and at one-half the peak value, and the resulting sediment-discharge graph was integrated to obtain the volume. Similarly, when $Q_p/b>10$, the sediment discharge was obtained for the peak discharge and at one-third and two-thirds of the peak value. This scheme preserved some of the nonlinearities involved in the sediment-discharge computations.

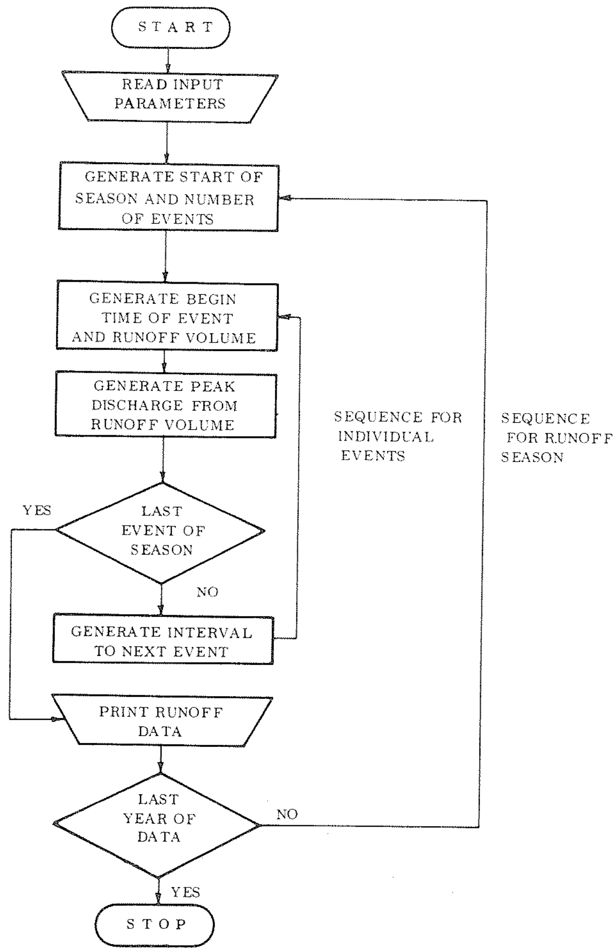

FIGURE 3.—Flow chart of synthetic data generation process. (From Lane and Renard, *16*.)

MODEL VERIFICATION

Methods for analysis and comparison of observed and synthetic runoff data from semiarid watersheds have been developed and tested (*16*). Three 50-yr sets of synthetic runoff data were generated on a 36.7-mi^2 subarea on the Walnut Gulch watershed and compared with the shorter sequence of observed data. Two comparisons were necessary to judge the degree of correspondence between the statistics of the actual and synthetic data for those parameters used in the generation process. This correspondence was good. Parameters not used as direct input to the model were also compared. Four such comparisons are shown on table 2. The means and standard deviations should agree, and the ranges in the longer synthetic data sets should exceed those of the shorter observed data set. Peak-discharges and length-of-season ranges satisfy this hypothesis, but annual volumes agree better. The most serious differences in table 2 are between the standard deviations of the season length for the observed and synthetic data, suggesting a need for an added constraint on season length within the model.

The comparisons between observed and synthetic runoff data indicate that the model generates data comparable to the observed data with respect to the comparison criteria (table 2), except for the variability in season length. However, the mean values of season length correspond, allowing the use of this runoff model in the sediment-yield calculations. Of primary importance was the preservation of maximum annual discharge and annual runoff volume means and standard deviations.

Sediment-discharge data are difficult to obtain in ephemeral streams because (1) the flow depths change rapidly, (2) the high stream velocities make it difficult to obtain an aliquot of the water-sediment mixture by conventional depth-integrating samplers, and (3) high debris loads clog samplers and impair sampler operation. Depth-integrated samples obtained intermittently at flumes 1 and 6 on the Walnut Gulch Experimental Watershed (fig. 2) were used. Samples at these two gaging sites were obtained with a USD-48 hand sampler by wading across the stream at low discharges. At high stages, a USP-63 depth-integrating sampler was lowered from a cableway about 100 ft upstream from the flume.

Synthetic values of peak sediment discharge and storm sediment volume (suspended sediment only) are compared with actual measurements in figures 5 and 6 for the outlet of Walnut Gulch. The agreement between the actual and synthetic data is encouraging, although the snythetic

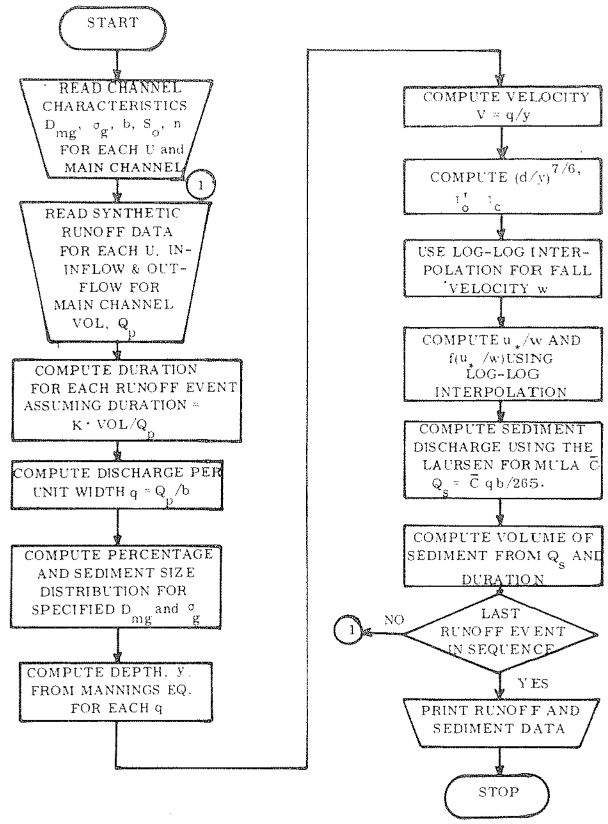

FIGURE 4.—Flow chart of sediment-discharge computation program.

TABLE 2.—*Comparison of parameters not used in generation of synthetic data*[1]

Runoff variable	Observed data (93 events)	Synthetic data Set 50-1 (605 events)	Synthetic data Set 50-2 (567 events)	Synthetic data Set 50-3 (578 events)
Peak individual discharge (ft^3/s):				
Mean	495	614	545	509
Standard deviation	1,114	1,699	1,322	1,483
Range	0–7,300	0–23,800	0–11,700	0–21,300
Maximum annual discharge (ft^3/s):[2]				
Mean	2,845	4,152	3,399	3,486
Standard deviation	2,390	4,212	2,732	3,656
Range	64–7,300	417–23,800	26–11,700	184–21,300
Annual runoff (inches):				
Mean	0.25	0.27	0.22	0.21
Standard deviation	0.24	0.21	0.18	0.16
Range	0.009–0.750	0.019–0.825	0.0002–0.670	0.017–0.852
Runoff season (days):				
Mean	59.2	64.6	60.6	60.5
Standard deviation	12.1	28.0	28.0	19.6
Range	41–80	16–137	1–150	23–118

[1] From Lane and Renard (*16*).
[2] Annual values based on 8 yr of historic data and 50-yr sets of synthetic data.

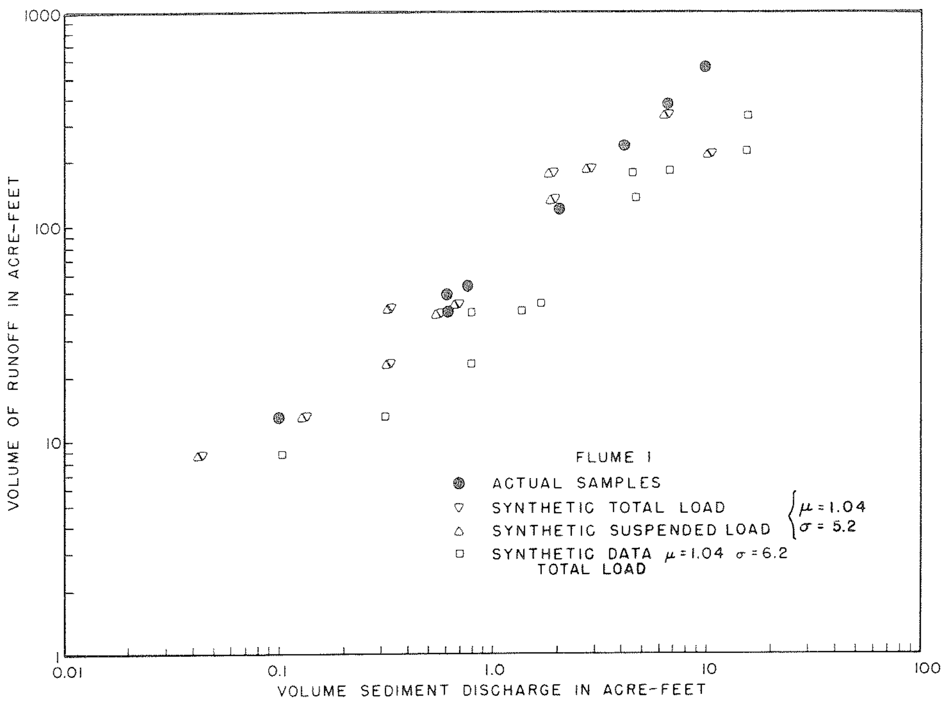

FIGURE 5.—Comparison of the synthetic and actual sediment yields for selected runoff events and bed-material size distributions by a log-normal probability relationship quantified by a mean diameter (μ) and standard deviation (σ).

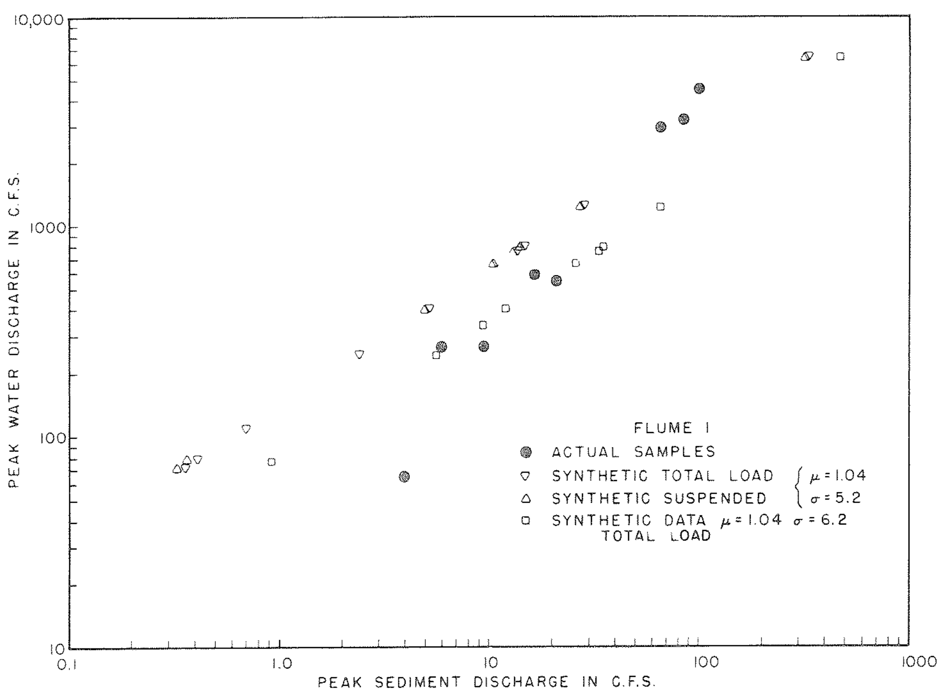

FIGURE 6.—Comparison of synthetic and actual peak sediment discharges for selected events on Walnut Gulch at flume 1 and bed-material size distributions by a log-normal probability relationship quantified by a mean diameter (μ) and a standard deviation (σ).

values are very sensitive to the bed-material size distribution represented on the figure by the mean grain size (μ) and the standard deviation (σ). The individual concentration-water discharge values, however, exhibit a wider scatter than that shown in these figures.

Figure 7 shows the concentration data for samples collected at the Walnut Gulch outlet during the 1970 summer monsoon season. As shown in this figure, the concentration for any instantaneous discharge varies considerably (almost a full log cycle). Tracing the pattern of consecutive samples for an individual flow event shows a typical "7," or loop, pattern. (See the short dash line connecting the open squares in the upper left portion of figure 7.) Thus, for example, the concentration remains essentially independent of discharge on the rising portion of the hydrograph and exhibits a more normal concentration line slope on the recession.

The lines shown on the graph are the concentration-discharge relationship for various bed-material size distributions computed by the Manning flow equation with the Laursen sediment-transport relation. The solid lines in the figure represent Manning roughness values of 0.025, and the dash lines represent roughness values of 0.020. The shaded portions illustrate the transport portion associated with the bedload as predicted from the Laursen relation for two size distributions and roughness values.

Sediment sizes of the material available for transport on the streambed vary considerably, both spatially and temporally. Figure 8 illustrates some of the variability encountered by sampling the channel material 100 ft upstream from the flume after each flow event in 1970, i.e., corresponding to the sampling periods shown in figure 7. Such sampling at equal increments across the stream showed wide variations in the mean size and some variation in the standard deviation. The log-normal distribution shown in this figure was used in the sediment concentration generating routine to obtain the percentage of material in various size increments, which simplified the computation scheme. Thus, although the extremes departed slightly from a straight-line theoretical distribution, these deviations were probably less than the errors associated with other assumptions. The importance of this size variation within a storm and within a season can be seen from the mean sediment size (μ) and the standard deviation (σ) used in figure 7 to label the individual concentration-discharge lines.

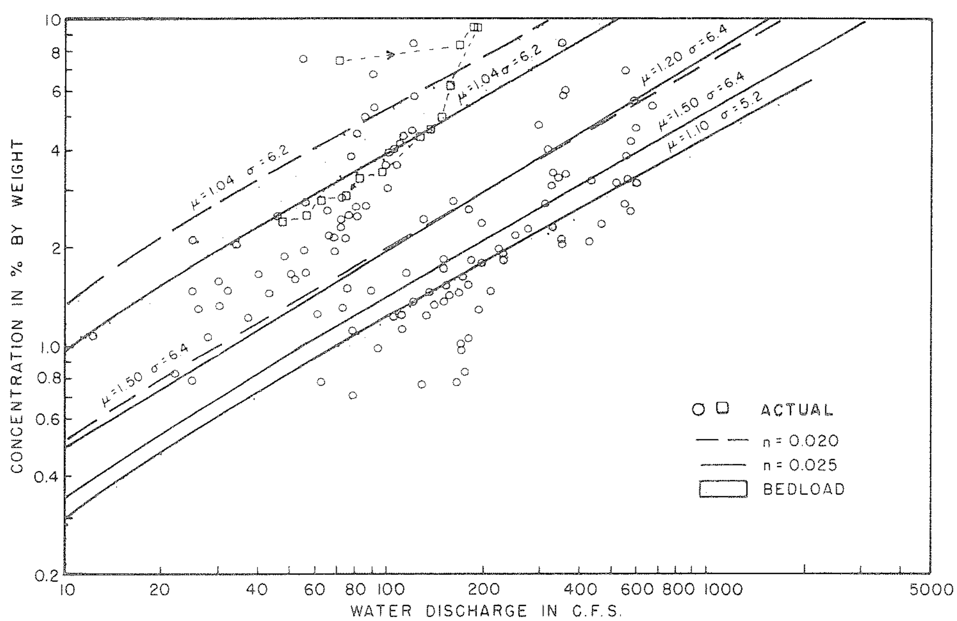

FIGURE 7.—Sediment concentration versus water discharge at flume 1 on Walnut Gulch. The circles are instantaneous values obtained by sampling in 1970, and the square connected by the dash line is a typical pattern associated with an individual runoff event. The solid and dash lines are values predicted with the Laursen transport relation for various size distributions given by the mean and standard deviations shown.

Synthetic runoff and sediment data were generated on watersheds 1 and 6. These 50-yr sets of synthetic data were formed by generating runoff data with the stochastic model described earlier and then by using these runoff data in the runoff-sediment model. The result of coupling a stochastic and deterministic model is again a stochastic sequence of runoff and sediment data.

The generation of synthetic data sequences is based on the premise that such data are adequate for predictive uses if (1) the synthetic runoff data are comparable to the actual data, (2) the runoff-to-sediment portion of the model is physically based, and (3) the synthetic sediment yield is comparable to prototype data.

Log-normal distributions were fitted to the synthetic annual runoff and sediment data generated with the model. A plot of annual runoff volumes is shown in figure 9 for 50-yr sequences of synthetic data on each of the two watersheds used in this study. The plotted points represent the synthetic runoff data and the line is a log-normal distribution fitted to the data. A similar plot for the synthetic annual sediment-yield data is shown in figure 10.

The volumes of sediment and runoff for any probability are larger for the larger watershed. This occurs even though the mean annual runoff (in inches from the watershed) was less for the larger watershed. The two theoretical lines diverge for the sediment data at the extreme.

Table 3 shows the variation in the annual runoff and sediment yield for various return periods. The annual sediment-yield data, expressed in inches, from the watersheds are surprisingly similar for each return period, although the runoffs differ. The similarity may indicate that ephemeral channels such as the Walnut Gulch channel react dynamically, adjusting the stream width and mean sediment size to maintain a quasi-equilibrium. Such a statement, however, is predicated on the assumption that the sediment size remains within limits, as shown in figure 8 and as used in the synthetic generation scheme.

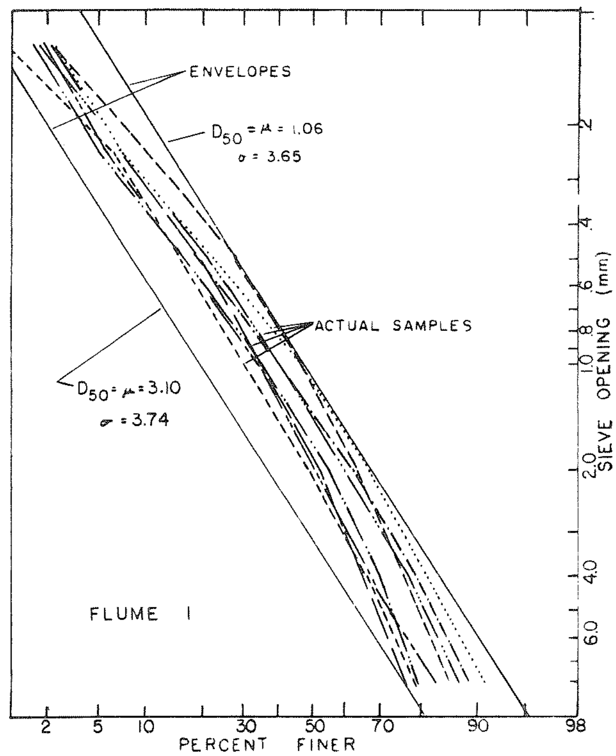

FIGURE 8.—Bed-material size distribution variation above flume 1 during the 1970 summer runoff season.

TABLE 3.—*Walnut Gulch: Return periods from 50-yr synthetic data sets*[1]

Return period (yr)	Watershed 1 (57.7 mi²)				Watershed 6 (36.7 mi²)			
	Annual runoff volume		Annual sediment yield		Annual runoff volume		Annual sediment yield	
	Acre-ft	Inch	Acre-ft	Inch	Acre-ft	Inch	Acre-ft	Inch
5	1,170	0.38	30	0.010	790	0.40	16	0.008
10	1,600	.52	47	.015	1,160	.59	28	.014
25	2,300	.75	76	.025	1,730	.88	51	.026
50	2,800	.91	100	.033	2,300	1.17	75	.038

[1] Based on a log-normal distribution for annual volumes.

RECOMMENDATIONS FOR FUTURE WORK

Although we believe that the model, tested on a single catchment containing several subwatersheds, is applicable to semiarid regions in the Southwest, additional work is needed to apply the model to a region. A regional model could be tied to physical and climatic characteristics, allowing synthetic runoff generation on ungaged basins where thunderstorms produce the principal runoff.

Because the sediment transport of the model appears to be so sensitive to the size distribution of the bed alluvium, efforts need to be directed to quantifying both the temporal and spatial variability of the bed material during an individual flow, as well as from one flow to another. Slight changes in the mean grain size and in the standard deviation when using a log-normal probability distribution caused major changes in the concentration predicted with the Laursen sediment-transport relationship. Such changes in the bed-material size distribution may explain the wide variability of the concentration obtained by field sampling and may allow closer agreement between the predicted and observed data.

Although a deterministic scheme was used to calculate the sediment concentration, it may be less deterministic than the runoff. Work is anticipated to let the mean (μ) and standard deviation (σ) have the characteristics of the sampled bed material with the μ and σ values randomly generated or related to the characteristics of the storm. Such a method will hopefully more adequately represent the prototype than the constant values used herein.

Subdivision of the rectangular cross section into a shape nearer that actually encountered in field conditions will facilitate quantifying variability of the flow depth and thus the water velocity and particle shear. Such an effort, however, is difficult to justify except at low discharges, since samples in the prototype are usually collected at an individual location in the cross section because of the rapid changes in the flow depth.

The sediment transport of the model is quite sensitive to the roughness value used in the Manning equation. For example, reducing the roughness from 0.025 to 0.020 had the same effect on the predicted sediment concentration as

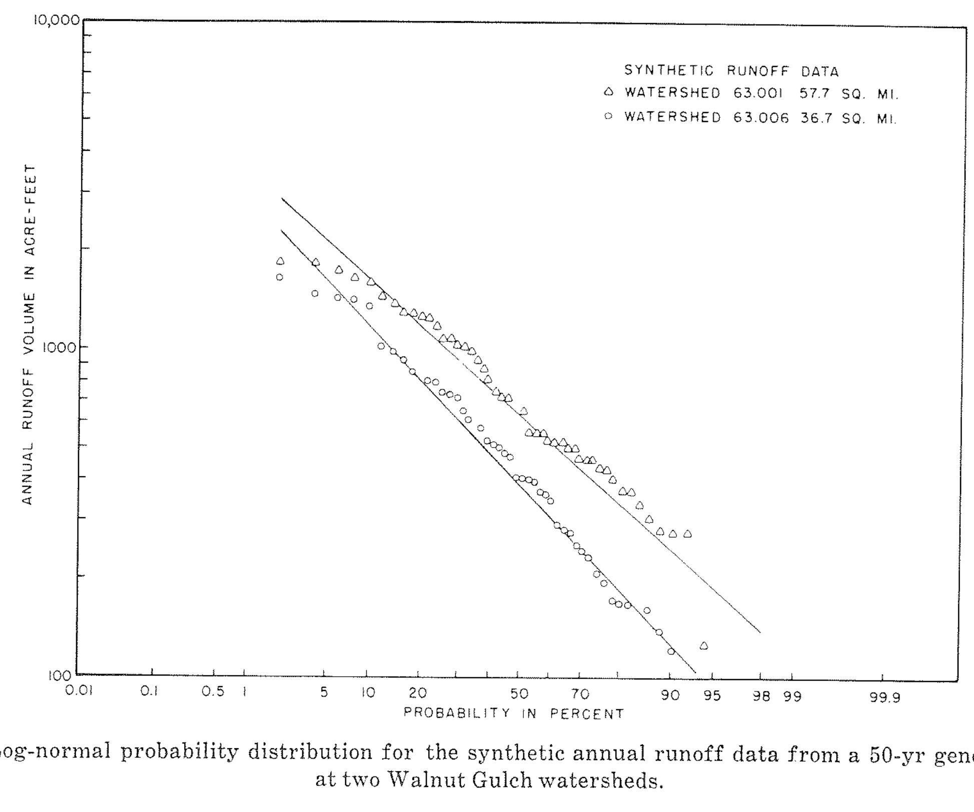

FIGURE 9.—Log-normal probability distribution for the synthetic annual runoff data from a 50-yr generated sample at two Walnut Gulch watersheds.

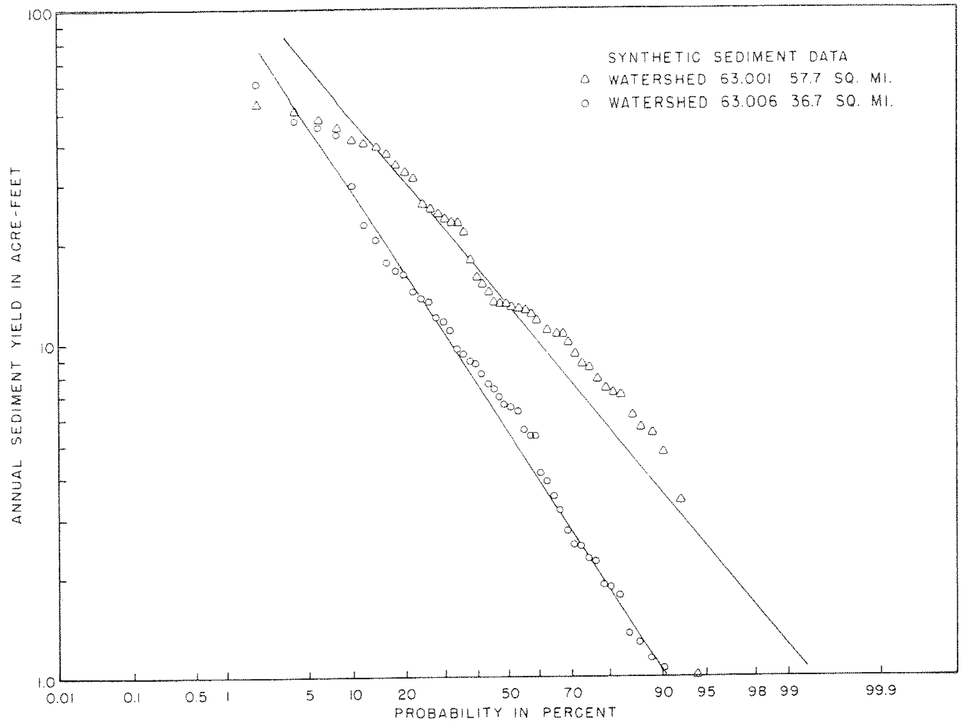

FIGURE 10.—Log-normal probability distribution for the synthetic annual sediment-yield data from a 50-yr generated sample at two Walnut Gulch watersheds.

reducing the mean grain size from 1.50 to 1.20 mm. Again, because of the difficulty of field verification, a numerical value for this parameter is difficult to obtain. Limited data in an instrumented channel reach revealed highly variable roughness values on the hydrograph rise because of the variability of transmission losses, which may absorb most of the rising portion of the hydrograph in a dry channel. At larger discharges, overriding waves tend to reduce the roughness and produce an artificially low roughness. Gross answers between tandem gaging stations indicate values approximating those used in this report, although the value at lower discharges is probably higher than the value used here. Again, braided flow and irregular cross sections make field observations difficult.

The runoff data of Walnut Gulch, which provided the numerical values used in the stochastic runoff model, are being retabulated. Eccentricities in the approach channel that are not time invariant have been modeled in a hydraulic laboratory. The results are being used to develop new prototype depth-discharge relationships. Thus, the mean and standard deviation in the normal distribution used to simulate the individual runoff event volume may change with the new information, although the changes are expected to be small compared to other assumptions used.

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